

DARK MATTER & SUSY: LEP RESULTS¹

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Abstract

The negative outcome of searches for supersymmetry performed at LEP have been used to derive indirect constraints on the parameters of the most plausible supersymmetric candidates for cold dark matter, in particular for the lightest neutralino. We review the basic ideas leading to the present lower limit on the lightest neutralino mass of about $37 \text{ GeV}/c^2$, with emphasis on the underlying assumptions.

1 Introduction

There are several hypotheses about the origin of the dark matter (see, for instance, Turner 1999). Among these, the possibility that the cold dark matter (CDM) is made, at least partially, of relic densities of elementary particles still survives if these particles are weakly interacting and massive ($\mathcal{O}(\text{GeV})$ or heavier) (Ellis 1998, Bottino 1999). The enlarged particle spectrum found in extensions of the Standard Model (SM) generally accommodates for Weakly Interacting Massive Particles (WIMP) that could become CDM candidates (Ellis 1998). A large number of dedicated experiments have been designed to detect the signal expected on earth detectors if the Galaxy halo is made of such particles. Most of these experiments look for the signal generated by the recoiling nucleus after a WIMP has interacted in low noise detectors, usually located underground. Other experiments look for WIMP annihilation leading to high energy neutrinos, high energy photons or antimatter in cosmic rays; for a review, see Feng 2000.

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A common feature of the experiments aiming at direct WIMP detection is the loss of sensitivity at low WIMP masses. For example, the first generation of Germanium experiments (Caldwell 1988) were sensitive to neutrino masses in the range $14 \text{ GeV}/c^2$ to a few TeV/c^2 . On the other hand, a relatively light WIMP could be produced directly or via decay cascades in collisions at accelerators. In standard particle detectors such particles would escape detection, just as neutrinos. The expected phenomenological signature would therefore be *missing energy*, i.e. effective energy-momentum non-conservation. The sensitivity of this indirect search for evidence of WIMP production is determined by three factors: *i*) the centre-of-mass energy (\sqrt{s}), which sets the mass scale of the particle that can be produced in the collisions; *ii*) the effective WIMP production coupling, which determines the production cross sections and therefore the rate of events; this is typically larger than the nucleon-WIMP coupling relevant for the direct searches, because of the larger energy scale involved; *iii*) the topology of the event, which determines the efficiency for detecting the interesting events; to be detected, in fact, WIMPs have to be produced in association with some visible, *triggering*, particle (Sect. 4). Once the triggering process is found, the indirect search has typically good sensitivity in all the kinematically allowed range, therefore representing a potentially important complement to direct searches at small WIMP masses.

The present accelerator experiments were not specifically optimized for this kind of searches, but have nonetheless some sensitivity to the predicted final states, mainly because of the good hermeticity which is the key point in determining the missing energy. Though the largest kinematical ranges are provided by hadronic colliders, the best sensitivity at present is reached by experiments at electron-positron colliders, which feature clean environments, allowing the study of all possible channels and their combined interpretation. In this paper we will focus on the CDM candidates predicted in supersymmetric extensions of the SM (reminded in Sect. 2) and on the constraints derived from the measurements done at the CERN LEP e^+e^- collider.

2 Supersymmetry and its CDM candidates

Supersymmetry (SUSY) is a symmetry relating bosons and fermions introduced in the building extensions of the SM to cure the so-called *hierarchy problem* (for reviews see Nilles 1984, Haber 1985, Martin 1997). The minimal particle content of a supersymmetric version of the standard model is shown in Table 1. Scalar partners (*sfermions*) are associated with ordinary matter fermions; the partners of gauge and Higgs bosons (*gauginos, higgsinos*) are spin 1/2 fermions. In realistic supersymmetric models, the exact mass degeneracy between standard particles and supersymmetric partners is broken by the so-called *soft* supersymmetry breaking (soft-SB) terms, which preserve the theoretical benefits of these theories. The minimal set of parameters needed to specify the model contains two parameters of purely supersymmetric nature - the ratio between the vacuum expectation values (vev) for the two Higgs doublets, usually denoted as $\tan \beta$, and a mass parameter μ governing the mixing between the two Higgs doublets - and a few soft-SB ones: three gaugino masses, $M_{i,i=1,2,3}$, associated with the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ groups, respectively, to complete the description of the gaugino sector, one mass term $M_{\tilde{f}}$ per scalar state and the third family trilinear couplings A_t , A_b , A_τ for the sfermion sector.

Sector		Quark	Lepton	EW Gauge/Higgs bosons		QCD	Gravity
SM	Spin	1/2	1/2	1	0	1	2
		$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R$	$\begin{pmatrix} \nu \\ l_L^- \end{pmatrix}, l_R^-$	γ, Z	h, H, A	W^\pm	H^\pm
SUSY	Spin Name	0	0	1/2	1/2	1/2	3/2
		Squark $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}, \tilde{u}_R, \tilde{d}_R$	Slepton $\begin{pmatrix} \tilde{\nu} \\ \tilde{l}_L^- \end{pmatrix}, \tilde{l}_R^-$	Neutralino $\chi_{i,i=1,\dots,4}^0$	Chargino χ^\pm, χ_2^\pm	Gluino \tilde{g}	Gravitino \tilde{G}

Table 1: *Particle content of a Minimal Supersymmetric extension of the SM*

The large number of additional parameters is reduced by imposing the unification conditions at scale M_{GUT} . For gauginos, at lowest order these read

$$M_1 : M_2 : M_3 : M_{1/2} = \alpha_1 : \alpha_2 : \alpha_3 : \alpha_{\text{GUT}} \quad (1)$$

where $m_{1/2}$ and α_{GUT} are a common gaugino mass term and the unifying coupling constant at M_{GUT} . For sfermions, the unification relations read

$$M_{\tilde{f}_i}^2 = m_0^2 + C_i m_{1/2}^2 + D_i (\tan \beta, M_Z, \theta_W) \quad (2)$$

where m_0 is a common sfermion mass term at M_{GUT} , and the C_i, D_i quantities depend on the quantum numbers of the sfermion. The trilinear couplings are also derived from a common trilinear coupling A_0 at M_{GUT} .

The experimental non-observation of any baryon number (B) or lepton number (L) violation suggests that there is no tree-level violation of those quantities. This is enforced by requiring the conservation of the quantum number $R = (-1)^{3(B-L)+2S}$ (S being the spin), implying that supersymmetric partners are produced in pairs, *i.e.* that the Lightest Supersymmetric Particle (LSP) is stable. Under the conservation of R parity, a neutral LSP is a natural candidate for CDM (Ellis 1983). By looking at Table 1 one can single out three possibilities: *i)* gravitinos: they are generally expected to be quite heavy, except in a special class of models called Gauge-Mediated-SB models, where they are predicted to be extremely light ($\sim \text{eV}/c^2$); in the latter case they would contribute to hot DM, which is disfavored; we will not consider them any longer; *ii)* sneutrinos: they can be the LSP with the only free parameter the mass $M_{\tilde{\nu}}$; the interesting ranges for CDM are $M_{\tilde{\nu}} \sim \text{few GeV}/c^2$ or $M_{\tilde{\nu}}$ in $[550, 2300] \text{ GeV}/c^2$ (Ellis 1998); the latter range is excluded by direct searches (Caldwell 1988); *iii)* neutralinos: the χ_1^0 is a flexible candidate for CDM, giving the correct relic density $\Omega_{\text{CDM}} h^2$ in large portions of the parameter space (see, for instance, Ellis 2000a and references therein), as can be seen in Fig. 1a.

3 LEP and its detectors

The LEP machine is a synchrotron electron-positron collider located at CERN in the surroundings of Geneva, Switzerland. The first operation phase (LEP 1, 1989-1995,

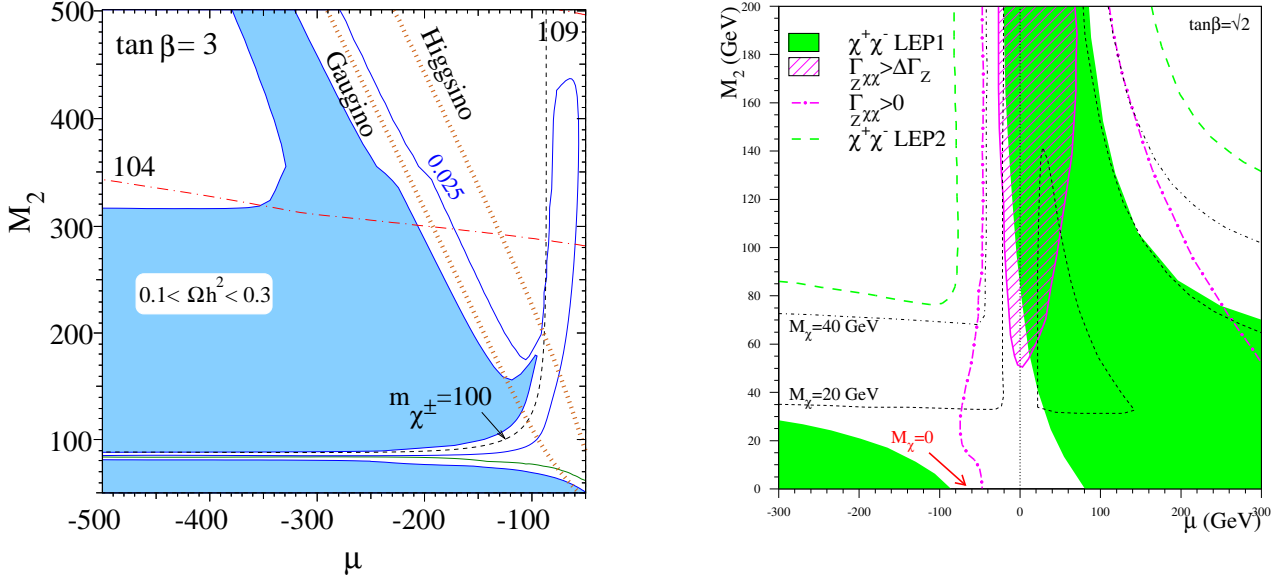


Figure 1: *Left:* Portions of the parameter space (μ, M_2) giving the relic density in the cosmologically preferred range $0.1 < \Omega_{\text{CDM}} h^2 < 0.3$ (light gray). Higgs boson and chargino mass contours are shown as dot-dashed and dashed lines, respectively. Here $\tan \beta = 3$, $m_0 = 1000$ GeV/ c^2 , $m_A = 1000$ GeV/ c^2 . From Ellis 2000a). *Right:* Basic features of the (μ, M_2) plane for $\tan \beta = \sqrt{2}$.

$\sqrt{s} = 88 \div 95$ GeV, ~ 175 pb $^{-1}$ /experiment collected) was dedicated to the precise measurement of the Z resonance. During the second phase, just completed, (LEP 2, 1995-2000, $\sqrt{s} = 130 \div 209$ GeV, ~ 650 pb $^{-1}$ /experiment collected) the machine was optimized for new particle discovery. The results discussed here are based on the data collected before 2000 at $\sqrt{s} \leq 202$ GeV.

The four detectors installed in the interaction points were designed for precision measurements. They feature a large covering of the solid angle (typically 80% for charged particles, 95% for neutrals), good lepton (electron, muon) identification, photon reconstruction and heavy flavor (b, τ^\pm) tagging, good hadron jet reconstruction capabilities. The total visible energy E_{vis} is usually measured with a resolution of $10\% \cdot \sqrt{E_{\text{vis}}}$. Finally, the trigger efficiency is typically 100% provided $E_{\text{vis}} > \sim 3$ GeV.

During the LEP 1 phase, a precise scan of the Z resonance was performed, allowing a precise determination of the Z parameters to be done. The parameters of the Z boson, in particular the Z widths, are expected to be modified by the opening of the new potential decay channels predicted in the MSSM. By comparing the most recent determination of the Z widths (LEP EW 2000) with the predictions, 95% confidence level upper limits of 6.2 and 1.7 MeV on new contributions to the total and invisible Z widths, respectively, can be derived. These exclude Heavy Dirac or Majorana neutrinos and sneutrinos masses up to about 40 GeV/ c^2 . In particular, the precision measurements definitely rule out the sneutrino as supersymmetric candidate for CDM (see Sect. 2), representing a good example of complementarity between indirect and direct searches.

4 Constraining the neutralino: basic idea

The precise measurements of the Z resonance do not set absolute constraints on the parameters of the χ_1^0 because it is possible to find configurations in the parameter space where the coupling associated with $Z\chi_1^0\chi_1^0$ vertex is very small. Direct search for $\chi_1^0\chi_1^0$ events would of course not help since they would not be recorded by the detectors. In such cases, sensitivity to χ_1^0 parameters can be recovered by looking at other processes predicted by the model for a given set of parameters. In this section we present the basic ideas underlying the analysis; more details are given in Sect. 5. The GUT relations introduced in Section 2 (Eq. 1) establish a link between M_1 and M_2 , $M_1 = \frac{\alpha_1(m_Z)}{\alpha_2(m_Z)}M_2 \sim \frac{M_2}{2}$, so that the properties of both the chargino and neutralino sectors are described in terms of $\tan\beta$, μ and M_2 . Exact formulae for mass matrices can be found in the literature (see, for instance, Haber 1985). Of relevance here is the approximate relation $m_{\chi_1^0} \propto \text{Min}(M_2, |\mu|)$, which implies that an absolute sensitivity to $m_{\chi_1^0}$ requires sensitivity to the model predictions for M_2 , $|\mu| \sim 0$ ³. As it was first noticed in Ellis 1996, the common gaugino description can be used to derive constraints on the neutralino sector from the results of searches for chargino pair-production. This works particularly well when the sfermions are heavy, i.e. out of the LEP kinematic reach. In such a case (see Sect. 5.1) the LEP data exclude chargino pair production essentially up to the kinematic limit; at $\sqrt{s} \geq 130$ GeV this implies that parameter settings with $\mu=0$ or $M_2=0$ are incompatible with the data (see Fig. 1b), thus allowing an absolute lower limit on $m_{\chi_1^0}$ to be derived⁴. In the case the sfermions are light, the reach of chargino searches is reduced (Sect. 5.2). However, the sfermions, in particular the sleptons, could be light enough to be in the LEP kinematic reach. The constraints of sleptons pair-production can be translated into constraints on the gaugino sector using the GUT relations for sfermion masses (Eq. 2); the loss of sensitivity of chargino searches is then partially backed up (Sect. 5.3). Finally, pushing further the use of the GUT relations for sfermion masses, stronger constraints on $m_{\chi_1^0}$ can be derived using the limits inferred on the squark sector from the negative results of Higgs boson searches (Sect. 5.4).

5 Direct searches at LEP 2

The analysis discussed in Sect. 3 is an example of indirect search for new phenomena. The *standard* processes, which constitute the *background* for the new physics ones, are measured as precisely as possible, and the result is compared with the prediction of the SM, looking for deviations. The sensitivity s to deviations is well approximated by $s = S/\sqrt{B}$, being S the signal yield expected and the B the residual background, and is therefore limited by the statistical fluctuations of the background which are typically large, since no attempt is done in the indirect searches to reduce it. The purpose of direct searches is to try to increase the sensitivity of the search by reducing

³Though both χ_1^0 mass and couplings are relevant for the calculation of $\Omega_{\text{CDM}}h^2$, the CDM constraints are usually given in terms of an absolute lower limit on $m_{\chi_1^0}$, valid, under the given assumptions, for all the field configurations.

⁴From Fig. 1b we see, *en passant*, that the kinematic reach of LEP 1 was not large enough to allow setting an absolute limit on $m_{\chi_1^0}$ at low $\tan\beta$ (Ellis 1996)

the background contamination keeping reasonable efficiency on the signal, so that s is increased. For practical reasons, most of the results used in this section are taken from the ALEPH publications (ALEPH 1998 and ALEPH 2000); however similar results have been obtained by the other LEP collaborations (DELPHI 2000b, L3 2000, OPAL 2000).

Production in e^+e^- collisions proceeds via s -channel exchange of a Z boson and, when allowed by quantum numbers, t -channel exchange of a supersymmetric particle (Fig. 2a,b). The relevance of the latter can be judged from Table 2, which gives the production cross-sections close to threshold and the \sqrt{s} dependence for a few representative processes. Chargino production has the largest cross-section, whatever the field composition, up to masses very close to the kinematical limit. However, the effect of a light sneutrino t -channel exchange, interfering destructively with the s -channel exchange, is significant, in particular in the so called gaugino region ($\chi^\pm \sim \tilde{W}^\pm$). For neutralinos and sleptons the interference can be constructive.

Process	$f(\beta_{\text{kin}})$	at $\sqrt{s} = 200$ GeV	Comments
$\chi^+\chi^-$	β_{kin}	2.1 pb 1.1 pb 0.5 pb 0.9 pb	$\chi^\pm \sim \tilde{W}^\pm$, heavy sneutrino $\chi^\pm \sim \tilde{H}^\pm$, heavy sneutrino $\chi^\pm \sim \tilde{W}^\pm$, $m_{\tilde{\nu}} = 50$ GeV/ c^2 $\chi^\pm \sim \tilde{H}^\pm$, $m_{\tilde{\nu}} = 50$ GeV/ c^2
$\chi_2^0\chi_1^0$	β_{kin}	0.4 pb	$\tan\beta=4$, $\mu=-95$ GeV/ c^2 , $M_2=500$ GeV/ c^2 $m_{\chi_2^0}+m_{\chi_1^0} = 195$ GeV/ c^2 , heavy selectron
$\tilde{e}_R^+\tilde{e}_R^-$	β_{kin}^3	0.13 pb	$\tan\beta=2$, $\mu=-100$ GeV/ c^2 , $M_2=100$ GeV/ c^2
$\tilde{\mu}_R^+\tilde{\mu}_R^-$	β_{kin}^3	0.04 pb	

Table 2: *Example cross sections. The produced particle mass is 95 GeV/ c^2 unless otherwise indicated.*

The decay patterns are depicted in Figs. 5d-f. For heavy sfermions, the decays of charginos and neutralinos are dominated by the exchange of W and Z, respectively, which at LEP energies are off-shell (3-body decays). The final states and the branching fractions will reflect those of the heavy bosonic mediators, thus with a predominance of hadronic final states. The graphs involving sfermions become of increasing importance as the sfermion masses decrease; eventually, when a sfermion is light enough to be produced on-shell in the decay (2-body decays) the corresponding process largely dominates over the 3-body decay processes.

We turn now back to the phenomenology of the final states. The χ_1^0 's interact only weakly and therefore escape detection. The fact that at least two of them are present in the final state gives apparent energy non-conservation, i.e. *missing energy*. This is the well known signature for supersymmetry under R-parity conservation. The *visible energy*, i.e. the energy carried by particles that can be detected, is directly related to the difference in mass $\Delta M = M - m_{\chi_1^0}$ between the produced particle and the χ_1^0 . Under the assumption of two body decays where the visible system has negligible mass, the visible energy can be approximated by

$$E_{\text{vis}} \simeq \frac{\sqrt{s}\Delta M}{4M} \left(1 + \frac{m_{\chi_1^0}}{M} \right) \quad (3)$$

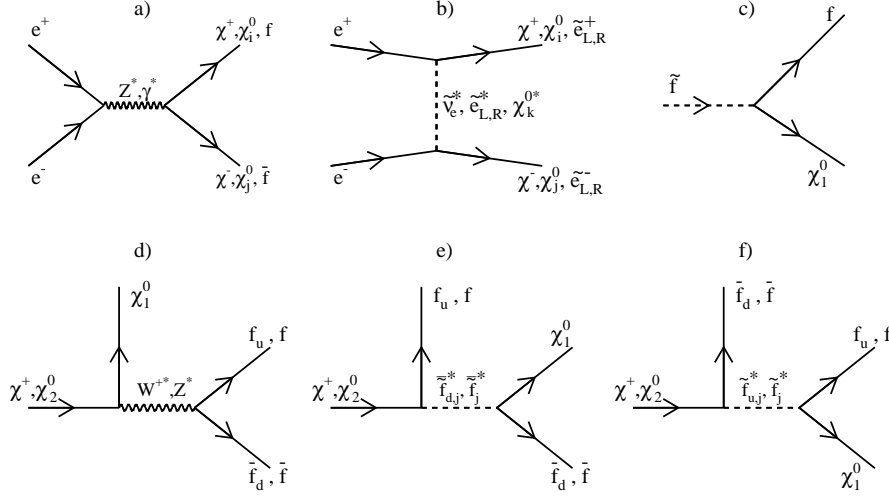


Figure 2: *Lowest order graphs for the relevant signal processes.*

There is, therefore, an intrinsic problem in detecting the signal when $\Delta M \rightarrow 0$, partially recovered by the boost for very small ΔM (like in $\tau^+\tau^-$ production, for instance), thanks to the Lorentz boost. Since the trigger needs at least 3-5 GeV of visible energy to have reasonable efficiency, we see from Eq. 3 that for particles close to the kinematic limit, direct searches will be blind for $\Delta M \leq 2-3$ GeV, unless very special trigger techniques are adopted. However, for the CDM constraints discussed in this paper, the problem is less severe, since, in the interesting regions (see Fig. 1b), the χ_1^0 is gaugino like with typically large ΔM 's.

5.1 Backgrounds

The background processes are those processes predicted by the standard model which can fake the signal, i.e. can have missing energy. In order of decreasing cross section these are:

$\gamma\gamma \rightarrow f\bar{f}$. The so-called *gamma-gamma* processes described at tree level by the graph shown in Fig. 3a. The initial state electron and positron are usually scattered at very low angle remaining undetected in the beam pipe. The remaining system can feature energy-momentum imbalance; however, its energy is typically small and the corresponding momentum non conservation limited. These processes have huge cross section ($\sim \text{nb}$) but they can be effectively reduced, and represent a problem only at very low ΔM .

$e^+e^- \rightarrow f\bar{f}(\gamma)$. These are shown in Fig. 3b and can have large cross sections (up to 100 pb). Except for the case $f=\nu$, which is not relevant here, these events can fake momentum imbalance only one final state particles is not well measured. In such a case they are reduced by requiring the direction of the missing momentum to be away from passive regions of the detector, like the beam line, for instance.

$e^+e^- \rightarrow f_1 f_2 \bar{f}_1 \bar{f}_2$. These are mediated by heavy gauge boson exchange and are

dominated by $e^+e^- \rightarrow W^+W^-$ (Fig. 3c,d). They have signal like cross sections (up to ~ 20 pb), and when $f_i = \nu$ they can feature very large transverse momentum (with respect to the beam axis) and missing energy, resulting very signal-like at large ΔM . Usually they can not be eliminated but have to be treated statistically in the evaluation of the result.

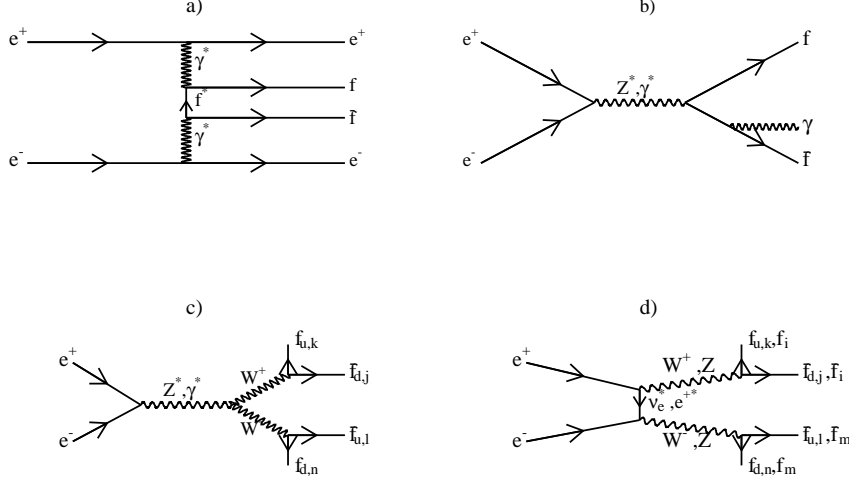


Figure 3: *Graphs of the main background processes.*

5.2 The main process: $e^+e^- \rightarrow \chi^+\chi^-$ with heavy sfermions

We start the discussion by assuming that the sfermions are heavy enough to make their effect on the cross section and decay processes negligible. For charginos in the reach of LEP 2 energies this corresponds to $m_0 \geq 200$ GeV if the GUT relations Eq. 2 are used for the sfermion masses. As we have seen above, the main decay process in this case is $\chi^\pm \rightarrow (W^\pm)^* \chi_1^0$ giving topologies similar to W^+W^- , with additional missing energy. The three main topologies searched for are given in Table 3 together with the main variables used to discriminate the signal, the residual background and the typical efficiency.

The absence of any excess above the standard mode expectation in the data collected up to 202 GeV (ALEPH 2000, DELPHI 2000b, L3 2000, OPAL 2000), allows each collaboration to set upper limits on the cross section for the specific process of the order of $(0.1 \div 1)$ pb, depending on the chargino mass and on ΔM . Translating in the (μ, M_2) plane for fixed $\tan \beta$ this result is sufficient to exclude chargino pair production up to the kinematic limit. This is shown, for example, in Fig. 4a for $\tan \beta = \sqrt{2}$. In particular the axis of the plane are excluded, which means that a lower limit on the χ_1^0 mass can be derived for each $\tan \beta$ value as shown in Fig. 4b. The result is basically determined by the kinematic limit for chargino production, and therefore is limited by the maximum centre-of-mass energy reached. It turns out that the lowest χ_1^0 mass is always reached in the gaugino-mixed regions of the (μ, M_2) plane, where the relation

Signal $\chi^+\chi^-\rightarrow$	Topology	Discriminating variables	ϵ (%)	Background	
				processes	σ_{bkg}
$\chi_1^0\chi_1^0 + u_i\bar{d}_j\bar{u}_n d_m$	jets + \cancel{E}	P_T, M_{vis}	~ 35	$Z\nu\nu, W\ell\nu,$ $\gamma\gamma \rightarrow q\bar{q}$	~ 45 fb
$\chi_1^0\chi_1^0 + u_i\bar{d}_j\bar{\nu}\ell^-$ + <i>h.c.</i>	jets + ℓ^\pm + \cancel{E}	$P_T, M_{\text{vis}}, \ell^\pm$ energy, ℓ^\pm isolation	~ 50	$W^+W^-, Z\gamma^*,$ $\gamma\gamma \rightarrow q\bar{q}$	~ 25 fb
$\chi_1^0\chi_1^0 + \nu\ell^+\bar{\nu}\ell^-$	$\ell^+\ell^-$ + \cancel{E}	$P_T, M_{\text{vis}},$ acoplanarity	~ 45	$W^+W^-, Z\nu\nu,$ $\gamma\gamma \rightarrow \ell\ell$	~ 150 fb

Table 3: *Typical performance of chargino searches at large m_0 . Here P_T is the total momentum transverse to the beam, M_{vis} the visible mass, ℓ^\pm an identified electron or muon; “jet” indicates collimated clusters of particles originating from the hadronization of quarks.*

$m_{\chi_1^0} \sim m_{\chi^\pm}/2$ is approximatively valid. The increment with \sqrt{s} of the mass limit is therefore given by $\Delta\sqrt{s}/4$, as can be verified in Fig. 4b.

The neutralino processes give final states topologically not much different from those predicted for charginos, which are selected with similar performances. However, since the cross sections are much smaller, their impact in the combined interpretation is visible only in a corner of the parameter space, namely at low $\tan\beta$ in the mixed region (Fig. 4b).

5.3 The light sfermion case

The GUT relations (Eq. 2) predict the sleptons lighter than the squarks and therefore to have the larger effect of gaugino phenomenology at LEP. Mixing in the stau sector could lead to some weird effect (LEP SUSY WG 1999); there is no systematic study of this available from the LEP collaborations. However there is enough information (DELPHI 2000a) to believe that even those bizarre complications could be dealt with without invalidating the general picture discussed here.

The qualitative effect of decreasing the sfermion masses is displayed in Fig. 4c, showing the ALEPH result for $\sqrt{s} \leq 189$ GeV and $m_0 = 75$ GeV/ c^2 . A qualitative comparison with Fig. 4a indicates that: *i*) the chargino sensitivity is reduced especially in the mixed region because of the smaller cross-section and the opening of 2-body decay channels that for very low ΔM lead to invisible final states; *ii*) the neutralino sensitivity somewhat enhanced for relatively large M_2 because of the larger cross-section, but it strongly decreased for large negative μ and relatively small M_2 because of the invisibility of the decay $\chi_j^0 \rightarrow \tilde{\nu}\nu$ which dominates in that region for low m_0 . The net result is that in the mixed region the sensitivity of the combined gaugino searches is reduced.

The inclusion of the sleptons using the GUT relations allows to recover the sensitivity lost by gaugino searches. Sleptons have been searched for mainly through the standard decay channel $\tilde{\ell} \rightarrow \chi_1^0\ell$, producing pairs of acoplanar leptons, and they would be selected with rather high efficiencies and relatively low backgrounds by all the four LEP detectors, in particular for the selectron and smuon channels. Cross section upper limits of the order of 0.025 pb, usually shown in the plane $(m_{\tilde{\ell}}, m_{\chi_1^0})$, have been obtained by the combination of the results. From these upper limits, mass lower limits

are derived, which can be superimposed to the gaugino constraints. For example, the ALEPH lower limit for $m_{\chi_1^0} \simeq 40 \text{ GeV}/c^2$ is about $93 \text{ GeV}/c^2$ (ALEPH 2000). Using the GUT relations (Eq. 2) and assuming no mixing in the stau sector, results like the one shown in Fig. 4c are obtained. The study of plots like these for different $\tan\beta$ and m_0 values allows the derivation of a lower limit of $m_{\chi_1^0}$ independent of m_0 . The L3 result is shown as a function of $\tan\beta$ in Fig. 4d (L3 2000).

Two comments about the figure. For $\tan\beta$ close to 1 the sensitivity obtained at small m_0 including the sleptons is better than the one reached at large m_0 by gaugino searches alone. In that $\tan\beta$ region Fig. 4d is therefore the same as Fig. 4a. For $\tan\beta > \sim 2$ the sleptons are not able to cover completely the *corridor*, the low $\Delta M (= m_{\chi^\pm} - m_{\tilde{\nu}})$ region where charginos are invisible. The limit shown in such case is obtained at small m_0 by slepton searches. However, this limit is better than the one obtained at large m_0 for $\tan\beta = 1$.

The absolute lower limit on $m_{\chi_1^0}$ using data collected at centre-of-mass energies up to 202 GeV is $37.5 \text{ GeV}/c^2$, reached at large m_0 for $\tan\beta = 1$. This result has been obtained using the lowest order GUT relations for $r = M_1/M_2$ at electroweak scale, calculated assuming no physics between the supersymmetry breaking and the grand unified scales, and no radiative corrections to gaugino masses. Even assuming that no new physics other than supersymmetry appears below the GUT scale, one should consider the inclusion of high order corrections to r and radiative corrections to the gaugino masses, each expected to affect by about 3% the lower limit on $m_{\chi_1^0}$.

6 Impact of Higgs searches

Finally we would like to comment on the impact of the searches for Higgs bosons. Under the assumption of GUT relations for sfermion masses, a link between the Higgs and gaugino sectors (absent at tree level) is introduced via the those squarks which are partners of heavy quarks, like the stops and sbottoms. These in fact induce large radiative corrections to the Higgs sector (see, for instance, Ellis 1991). The mass of the lighter state h is predicted to be $\leq 150 \text{ GeV}/c^2$ and extensive searches have been performed at LEP for the lighter Higgs boson states, in particular in the channels $e^+e^- \rightarrow hZ$ and $e^+e^- \rightarrow hA$. From the negative results of such searches a lower limit of the order of $110 \text{ GeV}/c^2$ has been set of the mass of the lighter neutral scalar Higgs boson ⁵. Setting a lower limit on m_h translates into a lower limit, for example, on $m_{\tilde{t}}$, which in turn can be interpreted as a constraint in the (m_0, M_2) plane via the relevant Eq. 2, and combined with the constraints from gaugino searches as in the case of sleptons. Of course the result will depend not only on $\tan\beta$ but also on the chosen value for m_A and $A_{\tilde{t}}$. A scan over these two parameters has shown that the strength of the Higgs results are such that at low $\tan\beta$ there is indeed an improvement in the sensitivity to $m_{\chi_1^0}$, acting as a cut-off at $\tan\beta \simeq 2$ (see ALEPH 2000). However, there is no general improvement at large $\tan\beta$ where the limit is set in the corridor by the sleptons searches.

⁵During 2000 a hint for a $115 \text{ GeV}/c^2$ mass Higgs boson has been found by the LEP experiments (LEPC 2000); the possible implications of such findings on supersymmetric CDM are discussed, for instance, in Ellis 2000b.

7 Conclusions

Under the assumptions leading to the simplest GUT relations for the supersymmetric parameters and of R-parity conservation, the LEP searches for supersymmetry allowed to set an absolute lower limit of 37.5 GeV on the mass of the best accredited supersymmetric candidate for CDM, the lightest neutralino χ_1^0 , using the data collected up to 202 GeV. These kind of analyses complement the direct searches for CDM, usually less sensitive or even insensitive to very low WIMP masses. The absolute lower limit suffers of theoretical uncertainties of the order of a few GeV, and is mainly determined by the kinematic limit for chargino pair production (at small $\tan\beta$) and the constraints on slepton pair production (at large $\tan\beta$). Stronger constraints can be obtained at small $\tan\beta$ by the inclusions of the results of Higgs bosons searches. Finally, the interpretation of the non-observation of signals for supersymmetry in the last sample of LEP data collected during the year 2000 (LEPC 2000), is not expected to improve significantly on the present results; hence the results presented here can be considered to be a good approximation of the final ones.

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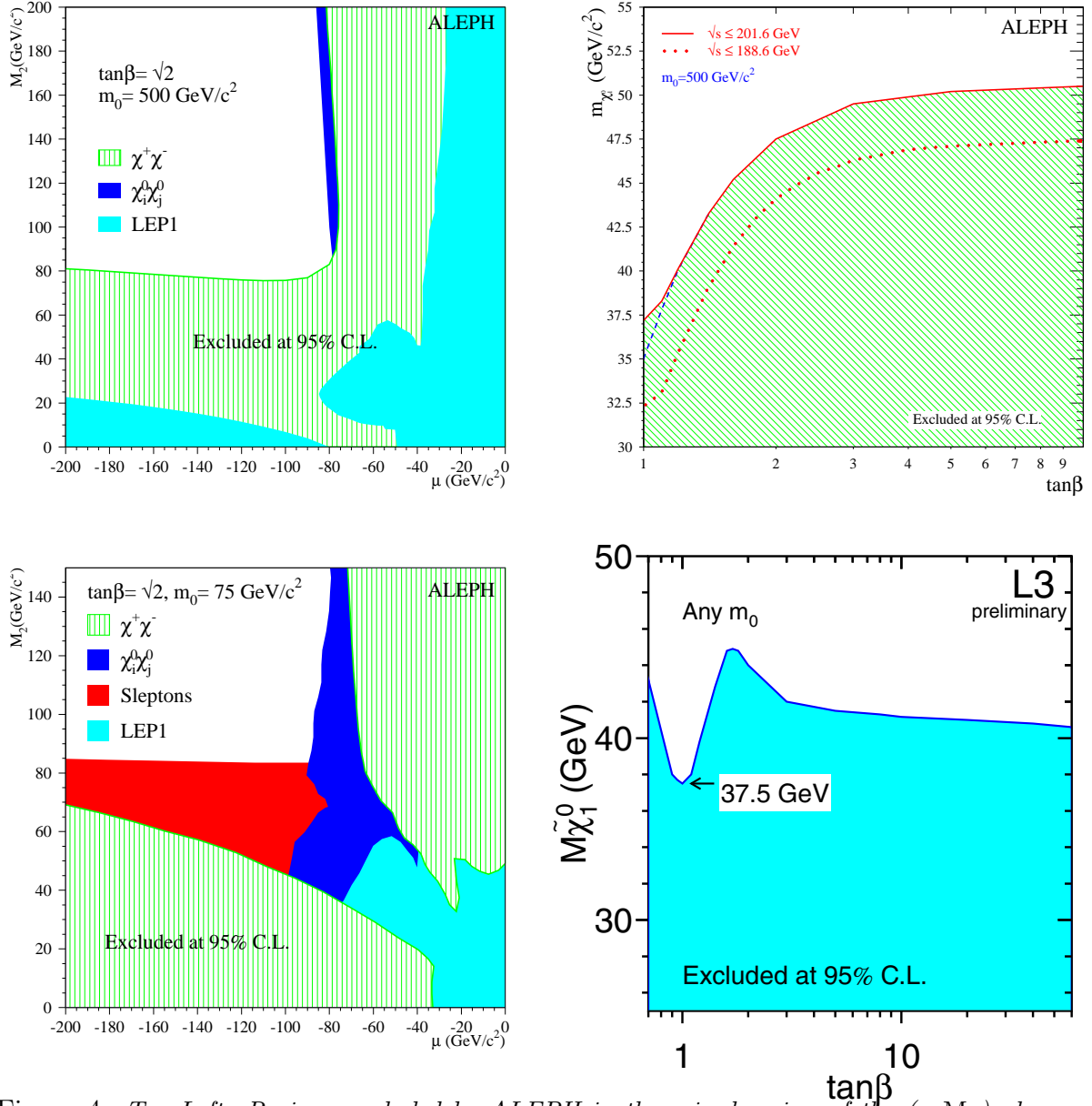


Figure 4: *Top-Left:* Regions excluded by ALEPH in the mixed region of the (μ, M_2) plane for $\tan\beta = \sqrt{2}$ using data collected up to $\sqrt{s}=202$ GeV and under the assumption of heavy sfermions (Ref. ALEPH 2000). *Top-Right:* The lower limit on $m_{\chi_1^0}$ as a function of $\tan\beta$ set by ALEPH under the assumption of heavy sfermions using data collected up to $\sqrt{s}=202$ GeV. The result obtained using the data up to $\sqrt{s} = 189$ GeV are shown for comparison (Ref. ALEPH 2000). *Bottom-Left:* Light sfermions scenario: sensitivity in the (μ, M_2) plane of the ALEPH searches at $\sqrt{s} \leq 189$ GeV for $m_0 = 75$ GeV/c² (Ref. ALEPH 1998). *Bottom-Right:* The lower limit on $m_{\chi_1^0}$ as a function of $\tan\beta$ set by L3 valid for any value of the common sfermion mass m_0 obtained using data collected up to $\sqrt{s}=202$ GeV (Ref. L3 2000).